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Accurate Binding of Sodium and Calcium to a POPC Bilayer by Effective Inclusion of Electronic Polarization

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Abstract

Binding affinities and stoichiometries of Na^+ and Ca^{2+} ions to phospholipid bilayers are of paramount significance in the properties and functionality of cellular membranes. Current estimates of binding affinities and stoichiometries of cations are, however, inconsistent due to limitations in the available experimental and computational methods. In this work, we improve the description of the binding details of Na^+ and Ca^{2+} ions to the 1-Palmitoyl-2-oleoyl-phosphatidylcholine (POPC) bilayer by implicitly including electronic polarization as a mean field correction, known as the electronic continuum correction (ECC). This is applied by scaling the partial charges of a selected state-of-the-art POPC lipid model for molecular dynamics simulations. Our improved ECC-POPC model reproduces not only the experimentally measured structural parameters for the ion-free membrane, but also the response of lipid head group to a strongly bound cationic amphiphile, as well as the binding affinities of Na^+ and Ca^{2+} ions. With our new model we observe on the one side negligible binding of Na^+ ions to POPC bilayer, while on the other side stronger interactions of Ca^{2+} primarily with phosphate oxygens, which is in agreement with the previous interpretations of the experimental spectroscopic data. The present model results in Ca^{2+} ions forming complexes with one to three POPC molecules with almost equal probabilities, suggesting more complex binding stoichiometries than those from simple models used to interpret the NMR data previously. The results of this work pave the way to quantitative molecular simulations with realistic electrostatic interactions of complex biochemical systems at cellular membranes.

Introduction

Interactions of ions with cellular membranes play a key role in many important biological processes.^{1,2} Ions, especially multivalent cations, modify general properties of the membrane which also modulate the embedded transmembrane proteins.²⁻⁴ For example, Ca^{2+} is crucial in propagation of neural signals. It promotes membrane fusion by bridging lipids in the vesicles carrying neurotransmitters and the neuron synapsis membrane.^{5,6} Ca^{2+} also participates in the T-cell receptor activation. It induces the detachment of the positively charged cytosolic tails of the CD3

protein complex from the negatively charged intracellular membrane making it accessible for the Lck protein.⁷ Another example involving sugar-lipid interactions mediated by ions concerns Ca^{2+} modulating the presentation of the sugars present in the $\text{PI}(4,5)\text{P}_2$ lipid which ultimately modulates the phospholipase C delta 1 pleckstrin homology domain (PLC $\delta 1\text{-H}$).⁸ Interestingly, this effect is not present for Mg^{2+} , which illustrates the selectivity of these processes with respect to particular ions. Despite our increasing understanding of the role of ions in cell membrane-related processes the molecular details of the mechanisms behind such processes remain elusive in many cases.

Direct measurements of ion-membrane interactions in complex biological systems are difficult. Hence, simplified lipid bilayers are often used as entry-level models to shed light on the role of ions in complex biological membranes.^{1,2,9} For this reason, interactions of biologically relevant cations, in particular Na^+ and Ca^{2+} , with zwitterionic phosphocholine (PC) bilayers have been widely studied experimentally^{1-4,10-13} and using molecular dynamics (MD) simulations.¹⁴⁻²⁵ The details of ion binding are, however, not fully consistent in the literature. Non-invasive spectroscopic methods, like nuclear magnetic resonance (NMR), scattering, and infrared spectroscopies mostly suggest that Na^+ ions exhibit negligible binding to PC lipid bilayers. In contrast, Ca^{2+} is observed to specifically bind to a couple of PC molecules via their phosphate groups.^{4,10-13,26-28} Most atomistic resolution MD simulation models predict stronger membrane bindings of the cations than observed in experiments.²⁹ Namely, simulations report various degrees of Na^+ accumulation at the lipid interface¹⁴ and for Ca^{2+} strong binding to up to four PC lipids simultaneously, involving not only interactions with phosphates but also with carbonyl oxygens.^{15,24,25}

Recent studies within the NMRLipids project (nmrlipids.blogspot.fi)²⁹ made an attempt to resolve these disagreements. A direct comparison of ion binding affinities to PC bilayers between simulations and experiments has been made possible using the electrometer concept.³⁰ Namely, the changes in NMR order parameters of the head group upon addition of ions are directly compared to the MD simulations results. Analyzing massive amounts of data collected within an open collaboration approach, it was concluded that the accuracy of the current state-of-the-art lipid models for MD simulations is not sufficient for a detailed interpretation of the interactions of

cations with PC lipid bilayers.²⁹

In this work, we improve the description of cation binding to a POPC bilayer within MD simulations via an implicit inclusion of electronic polarizability in the polar region of phospholipids. To this end, we apply the electronic continuum correction (ECC),³¹ within which scaling of the atomic partial charges is employed to account for the missing electronic polarizability in standard force field MD simulations. Such an approach has been shown previously to improve the behavior of ions in simulations of aqueous salt solutions.^{32–35} Here, we extend the ECC approach to aqueous lipid membranes taking the Lipid14 force field³⁶ as a starting point for refining the POPC model. This choice is justified by the fact that the Lipid14 provides the least inaccurate descriptions of cation binding among the existing force fields.²⁹ The newly developed ECC-POPC model reproduces the experimentally measurable structural parameters of an ion-free POPC lipid bilayer with the accuracy comparable to the best state-of-the-art lipid models, while at the same time significantly improving the membrane binding affinities of sodium and calcium cations.

Methods

Electronic continuum correction for lipid bilayers

The lack of electronic polarizability in standard MD force fields has been considered a serious issue since the early days of lipid bilayer simulations. In this work, we circumvent the demanding explicit inclusion of electronic polarization effects^{37,38} by accounting for the electronic part of polarizability in lipid bilayer simulations implicitly via the electronic continuum correction (ECC).³¹ Technically, this is similar to the phenomenological charge-scaling applied in earlier studies of surfactants, lipids or ionic liquids.^{39–41} However, the present concept of ECC is physically well justified and has theoretical support.^{31,42–44}

According to ECC, the electronic polarizability can be included into non-polarizable MD in a mean-field way by embedding the ions in a homogeneous dielectric continuum with a dielectric constant ϵ_{el} , which is the electronic part of the dielectric constant of the medium.³¹ Following

Coulomb’s law, ECC can be directly incorporated by scaling the charges with a constant scaling factor of $f_q = \epsilon_{el}^{-1/2}$, yielding

$$Q^{ECC} = f_q \cdot Q \quad (1)$$

for the ECC corrected charges. Given that the high frequency dielectric constant of water is $\epsilon_{el} = 1.78$ (*i.e.*, the square of the refraction index), the scaling factor for ions in water is roughly $f_q \approx 0.75$. This scaling factor significantly improves the accuracy of simulations of solvated ions, when quantitatively compared with neutron scattering data.^{32–35} It is important to note that the value of the high frequency dielectric constant is around 2 for almost any biologically relevant environment.³¹ The dielectric discontinuity in a lipid bilayer thus arises only from the orientational polarization of the molecules, which is accounted for explicitly in standard MD simulations. Therefore, the same correction for the electronic polarizability can be applied throughout the lipid bilayer/aqueous solution interface.

While using the scaling factor of $f_q = 0.75$ for ions in water is well justified in the ECC theory,³¹ it is not clear whether the same factor should be applied to partial charges used to describe molecules in MD models, *e.g.*, lipids in our case.⁴⁴ Unlike the total charge of an ion, atomic partial charges within molecules are not physical observables. Several computational schemes exist for the assignment of partial charges for biomolecules,⁴⁵ with the restrained electrostatic potential method (RESP) being commonly used.^{46,47} Considering that water is often included in RESP calculations or charges are refined to improve certain experimental observables, the electronic polarizability effects of the solvent may to some extent be included in standard force fields.^{46–50} Thus, our application of the scaling factor, f_q , to existing partial charges in molecules does not necessarily follow $f_q = \epsilon_{el}^{-1/2}$. Instead, a consistent scaling factor should lie between the value of 0.75 (*i.e.*, no electronic polarizability included in the original partial charges) and 1 (*i.e.*, electronic polarizability fully included in the original partial charges).

Here we develop a ECC-POPC lipid model that accurately describes binding of sodium and calcium ions to the POPC lipid bilayer. The Lipid14³⁶ force field (available in a Gromacs format from Ref. 51) was used as a starting point since it provides the most accurate response of the

head groups to ions among the available lipid models (see Figs. 2 and 5 in Ref. 29). Additionally, the Lipid14 model provides relatively realistic head group, glycerol backbone, and acyl chain structures.^{36,52} We applied the ECC correction to the Lipid14 model of POPC by scaling partial charges of the head group, glycerol backbone, and carbonyl regions. These are the polar parts of phospholipids which can contribute to the cation binding. A similar approach is also applied to the CHARMM36 model of POPC⁵³ in the the SI.

To reproduce the experimental ion binding affinities, we scanned possible values of the scaling factor from the interval $f_q \in (0.75, 1.0)$. The ion binding affinity was benchmarked against experiments using the head group order parameters and the electrometer concept,^{29,30} as discussed more detail in the next section. Scaling down the partial charges reduced the ion binding affinity. We found the most accurate ion binding affinities with a scaling factor of $f_q = 0.8$, which is only slightly higher than the ECC one ($f_q = 0.75$). Note that common empirical scaling factors for monovalent ions in water are 0.8 or even closer to unity.^{50,54,55} In contrast, modern force fields for ionic liquids suggest values of 0.6–0.65, which are lower than $\epsilon_{el}^{-1/2}$.⁵⁶ Directly applying the 0.8 scaling to the partial charges of the head group, the glycerol backbone, and the carbonyls reduced the area per lipid to 60 \AA^2 . This area is smaller than in the original Lipid14 model ($65.6 \pm 0.5 \text{ \AA}^2$)³⁶ and in experiments (64.3 \AA^2).⁵⁷ The decrease of the area per lipid arises from a reduced hydration of the lipid head group region after scaling of the partial charges, which effectively reduces the head group polarity. We solve this problem by slightly reducing the effective radii of the modified head group atoms via lowering the σ parameters in the Lennard-Jones potential by a factor of $f_\sigma = 0.89$. The same approach was successfully adopted for the ECC ions in aqueous solutions previously.^{32–35} After reducing the head group atoms σ parameters, the area per molecule is restored to the experimental value (Table 1).

Electrometer concept

Comparing MD simulation to NMR experiments, we can validate the ion binding affinity in lipid bilayer simulations using the 'electrometer concept'.^{29,30} This method is based on the experimental

observation that the C-H bond order parameters of α and β carbons in a PC lipid head group (Fig. 1) are proportional to the amount of charge bound per lipid.³⁰ The order parameters for all C-H bonds in lipid molecules can be accurately measured using ^2H NMR or ^{13}C NMR techniques.⁵⁸ From MD simulations the order parameters can be calculated using the relation

$$S_{\text{CH}} = \frac{1}{2} \langle 3 \cos^2 \theta - 1 \rangle, \quad (2)$$

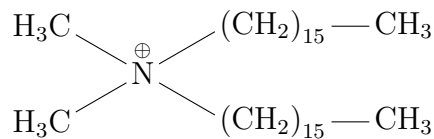
where θ is the angle between the C-H bond and the membrane normal. Angular brackets point to the average over all sampled configurations.

The relation between the amount of the bound charge per lipid, X^\pm , and the head group order parameter change, ΔS_{CH}^i , is empirically quantified as^{30,59}

$$\Delta S_{\text{CH}}^i = S_{\text{CH}}^i(X^\pm) - S_{\text{CH}}^i(0) \approx m_i \frac{4}{3\chi} X^\pm, \quad (3)$$

where i refers to either the α or β carbons, $S_{\text{CH}}^i(0)$ denotes the order parameter in the absence of bound charge, χ is the quadrupole coupling constant ($\chi \approx 167$ kHz), and m_i is an empirical constant depending on the valency and location of the bound charge.

The measured change of the order parameter depends on the head group response to the bound charge and on the amount of the bound charge (*i.e.*, m_i and X^\pm in Eq. 3, respectively). The empirical factor m_i has to be adequately quantified before the electrometer concept can be used to analyze the binding affinities. This calibration has been done experimentally for a wide range of systems.^{30,60} To calibrate the response of the head group order parameters to the bound charge in simulations, we use experimental data for a strong cationic surfactant dihexadecyldimethylammonium bromide (DHAB) mixed with a POPC bilayer.⁶¹ DHAB



is a cationic surfactant having two acyl chains and bearing a unit charge at the hydrophilic end.

Due to its structure it is expected to locate in the bilayer similarly to the phospholipids and its molar ratio then gives directly the amount of bound unit charge per lipid X^\pm in these systems.⁶¹

Salt concentrations and binding affinities

When measuring head group order parameters, the NMR experiments report the employed salt concentrations in two different ways. Some studies provide the salt concentrations in water before solvating the lipids,¹⁰ C'_{ion} , while others use atomic absorption spectroscopy and report the salt concentration in the supernatant after the solvation of lipids,¹¹ C_{ion} . In this work, we stick to the latter definition by estimating the salt concentration in the aqueous bulk region using the farthest point from the lipid bilayer in the aqueous phase. Note that the former definition was used by some of us previously.²⁹ Although these two definitions provide somewhat different values when applied to Ca^{2+} concentrations, their particular choice does not affect the conclusions of this work in any significant way.

To quantify the ion binding affinities to a lipid bilayer, we calculate the relative surface excess of ions with respect to water, Γ_{ion}^{water} .⁶² Such a quantity compares the adsorption of ions to the adsorption of water molecules at the interface without the necessity of defining a Gibbs dividing surface between the membrane interior and the water bulk region. In our simulations, we only assume that the interface is located between the ion-free hydrophobic interior of the lipid bilayer and the aqueous region far from the membrane. Such a setup and the above definition of bulk ion concentrations provides a simple relation for the relative surface excess Γ_{ion}^{water} for simulations of lipid bilayers,

$$\Gamma_{ion}^{water} = \frac{1}{2A_b} \left(n_{ion} - n_{water} \frac{C_{ion}}{C_{water}} \right). \quad (4)$$

Here, n_{water} and n_{ion} are the total numbers of water molecules and ions in the system, C_{water} and C_{ion} are their respective bulk concentrations in the aqueous phase (estimated from the solution density of farthest point between periodic bilayers), and A_b is the area of the unit cell in the membrane plane. The total area of the interface is then twice the area of the membrane, i.e., $2A_b$, because the

bilayer has an interface at each of the two leaflets.

Validation of lipid bilayer structure against NMR and scattering experiments

The structures of lipid bilayers in simulations without ions were validated against NMR by calculating the order parameters for the C-H bonds and against X-ray scattering experiments by evaluating the scattering form factors. NMR order parameters validate the structures sampled by the individual lipid molecules with atomic resolution. The simulated order parameters were calculated for all C-H bonds in lipid molecules from Eq. 2. Scattering form factors validate the dimensions of the lipid bilayer (i.e., the bilayer thickness and area per molecule). Form factors were calculated using a relation

$$F(q) = \int_{-D/2}^{D/2} (\rho_{el}(z) - \rho_{el}^s) \cos(zq_z) dz, \quad (5)$$

where $\rho_{el}(z)$ is the total electron density, ρ_{el}^s is the electron density of the solvent far in the aqueous bulk, and z is the distance from the membrane center along its normal with $D/2$ being half of the unit cell size.

Simulation details

Simulations of POPC bilayers with aqueous ions

Simulations of a POPC bilayer in pure water or at varying salt concentrations consisted of 128 POPC molecules and approximately 50 water molecules per lipid in an orthorhombic simulation box with periodic boundary conditions. The SPC/E⁶³ water model was used in all ECC-POPC model simulations reported in the main text. This model was also used in the previous parametrization of ECC-ions^{32,33,35} because its lowered dielectric constant is consistent with the ECC concept.^{31,44} The robustness of our approach with other water models (OPC,⁶⁴ OPC3,⁶⁵ TIP3P,⁶⁶ TIP3P-FB and TIP4P-FB,⁶⁷ and TIP4P/2005⁶⁸) was verified and is presented in the Supporting Information (SI). Sodium, calcium, and chloride ions were modeled as ECC-ions with parameters

from Refs. 32,33. Scaled charges and Lennard-Jones radii for atoms forming the POPC lipid were derived in this work starting from the Lipid14 force field.³⁶ For comparison, simulations with the Lipid14 model³⁶ and ion models by Dang and coworkers^{69–71} or ECC-ions^{32,33,35} were also performed. The TIP3P water model⁶⁶ was used in all simulations with the original Lipid14 model. Simulation data for the Lipid14 model with Åqvist ions⁷² and the TIP3P⁶⁶ water model were taken directly from Refs. 29,73–76.

MD simulations were performed using the GROMACS⁷⁷ simulation package (version 5.1.4). The simulation parameters used in this work are summarized in Table S1 in the SI. Compatibility with the openMM simulation package⁷⁸ was also tested and is presented in the SI. For deposited trajectories and parameter files see Refs. 79–81.

Simulations of POPC bilayers with cationic surfactants

The topology of the dihexadecyldimethylammonium cation was created with the automated topology builder.⁸² The AmberTools program⁸³ was used to generate the Amber-type force field parameters. These parameters were then converted to the Gromacs format with the acpype tool.⁸⁴ The partial charges were manually modified in the non-scaled version to approximately match similar segments in Lipid14.³⁶ For simulations of cationic surfactants mixed with ECC-POPC, all charges of cationic surfactants were scaled by a factor $f_q=0.75$ consistently with the counterions. The Lennard-Jones radii were scaled with the same factor as for ECC-POPC, i.e. $f_\sigma=0.89$.

The cationic surfactants were randomly mixed among the phospholipids to form bilayer structures with mole fractions of 10%, 20%, 30%, 42%, or 50% of surfactant in the POPC bilayer. All these systems contained 50 POPC molecules per leaflet, 6340 water molecules, and 6, 14, 21, 35, or 50 surfactants per leaflet. Chloride counter ions were used in all the simulations, while bromide was the counter ion in the experiment.⁶¹ For POPC, either Lipid14 with TIP3P⁶⁶ or ECC-POPC with SPC/E⁶³ parameters were used. The first 20 ns of the total simulation time of 200 ns was considered as an equilibration period and was thus omitted from the analysis. We checked that a sufficient lipid exchange occurred during the simulations. For deposited trajectories and parameter

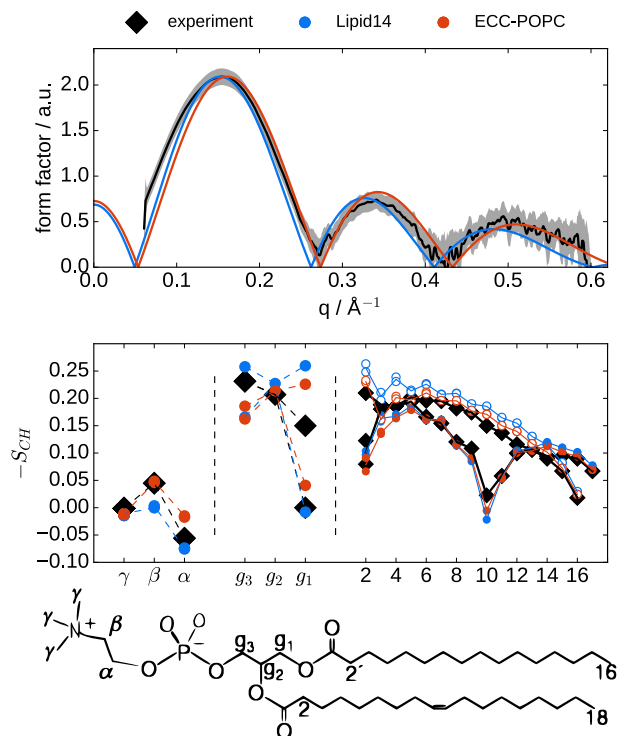


Figure 1: Top: X-ray scattering form factors from simulations with the Lipid14³⁶ and the ECC-POPC models compared with experiments⁵⁷ at 303 K.

Middle: Order parameters of POPC head group, glycerol backbone and acyl chains from simulations with the Lipid14³⁶ and the ECC-POPC models compared with experiments⁹² at 300 K. The size of the markers for the head group order parameters correspond to the error estimate ± 0.02 for experiments,^{52,58} while the error estimate for simulations is ± 0.005 (Bayesian estimate of 95% confidence interval⁹³). The size of the points for acyl chains are decreased by a factor of 3 to improve the clarity of the plot. Open/closed symbols are used for palmitoyl/oleoyl chains of POPC. Bottom: The chemical structure of POPC and the labeling of the carbon segments.

files of scaled and unscaled simulations see Refs. 85 and 86–91, respectively.

Results and Discussion

Structural parameters of a pure ECC-POPC model membrane: Agreement with experiments

First, we present results for bilayers in pure water. The ECC-POPC and Lipid14 models both reproduce the experimental X-ray scattering form factors of a POPC bilayer with a comparable

Table 1: Values of the area per lipid (APL) of POPC bilayers without ions.

| model | APL (\AA^2) | Temperature [K] |
|--------------------------|------------------------|-----------------|
| Lipid14 | 65.1 ± 0.6 | 300 |
| Lipid14 ³⁶ | 65.6 ± 0.5 | 303 |
| ECC-POPC | 63.2 ± 0.6 | 300 |
| experiment ⁵⁷ | 64.3 | 303 |

accuracy (see Fig. 1). The area per lipid from the Lipid14 model is by $\approx 1\text{\AA}$ larger than the experimental value in Table 1, while the value from the ECC-POPC model is by $\approx 1\text{\AA}$ smaller than the experimental one. The values of the area per lipid of the ECC-POPC model vary slightly when simulated with different water models (i.e., within the interval of 62.2–66.8 \AA , see Table S2 in SI), while still being close to the experimentally reported values. We can thus conclude that the ECC-POPC model reproduces the experimental dimensions of the POPC lipid bilayer with a comparable accuracy to other state-of-the-art lipid models.⁵⁸

Similarly, the acyl chain order parameters of the ECC-POPC model, as well as those of the Lipid14 model,³⁶ agree with the experimental values within the error bars, as presented in Fig. 1. Notably, the experimentally measured forking and small order parameter values of the C_2 segment in *sn*-2 chain are well reproduced by both models. This feature has been suggested to indicate that the carbonyl of the *sn*-2 chain is directed towards the water phase, in contrast to the carbonyl in the *sn*-1 chain, which orients more along the bilayer plane.^{94–96} This arrangement, which is not fully reproduced by other available lipid models,⁵⁸ may be a relevant feature for the ion binding details.

The order parameters of the α and β carbons in the head group are slightly larger in the ECC-POPC model than in the Lipid14 model, which is apparently related to the P-N vector orienting by about 7° more toward the water phase in the former model, see Fig. 2. While both models perform relatively well, considering the available experimental evidence, it is not possible to decide which of the two models provides more realistic head group orientations. The ECC-POPC model gives the β carbon order parameter value closer to experiments than the Lipid14 model, while the opposite is true for the α carbon. The accuracy of both models in the glycerol backbone region is comparable to other state-of-the-art lipid model available in literature,⁵² see Fig. 1. The

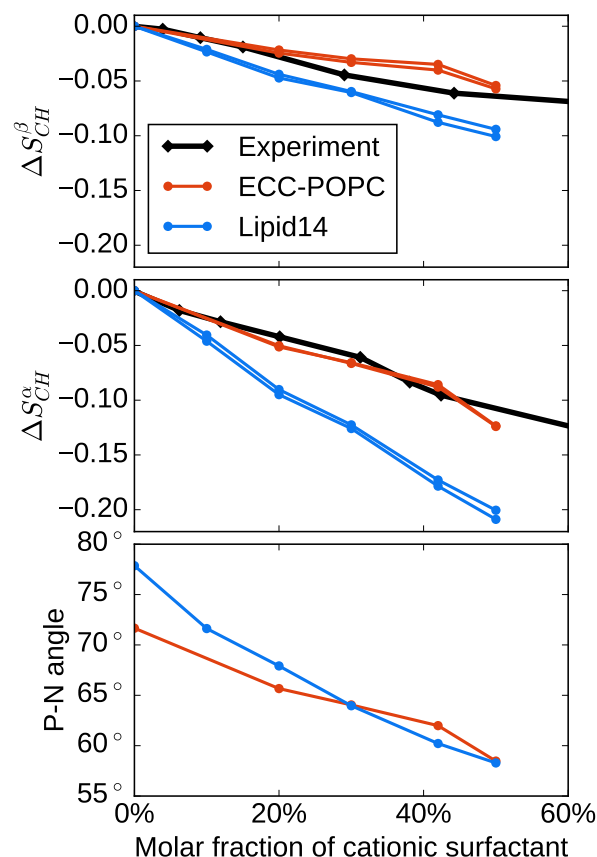


Figure 2: The changes of head group order parameters and P-N vector orientation as a function of a molar fraction of the cationic surfactant dihexadecyldimethylammonium in a POPC bilayer from simulations and experiments⁶¹ at 313 K.

electrostatic potentials as obtained in ECC-POPC and Lipid14 simulations are compared in the SI.

Calibration of head group response to membrane-bound charge using cationic surfactant

Before studying the sodium and calcium ion binding affinities, we quantify the response of the head group order parameters to the amount of bound charge by using mixtures of monovalent cationic surfactants (dihexadecyldimethylammonium) and POPC.⁶¹ These mixtures have a well-defined amount of bound charge per PC, namely, the molar fraction of cationic surfactants. This is due to the ability of dihexadecyldimethylammonium to directly insert in the lipid bilayer due to its two hydrophobic acyl chains. Furthermore, available experimental data for these systems can be

used to validate the sensitivity of lipid head group order parameters to the amount of bound charge in simulations.⁶¹

The changes of the head group order parameters with increasing amount of the cationic surfactant are compared between simulations and experiments⁶¹ in Fig. 2. An approximately linear decrease of the order parameters, as expected from Eq. 3, is observed in both simulations and experiments at least for mole fractions below $\sim 30\%$. The slope is, however, too steep in the Lipid14 model indicating that the response of head group order parameters to the bound positive charge is too strong. In contrast, the slope of the ECC-POPC model is in a very good agreement with experiments for the α segment, while being only slightly underestimated for the β segment.

In Fig. 2, we show the headgroup P-N vector angle as a function of the mole fraction of the cationic surfactant. As suggested previously³⁰ and observed in MD simulations,^{18,19,97,98} the headgroup orients more towards the water phase with the increasing amount of positive charge in the PC lipid bilayer. The effect is more pronounced in the Lipid14 model than in the ECC-POPC model. For example, the addition of 50% mole fraction of the cationic surfactant leads to a decrease of 20° of the P-N vector angle for the Lipid14 model while only of 11° in the ECC-POPC model. The difference is in line with the smaller order parameter changes and the reduced charge-dipole interactions in the latter model. The weaker sensitivity of the P-N vector angle response in the ECC-POPC model is in better agreement with experiments.

Validation of ECC-POPC model using binding affinities to Na^+ and Ca^{2+} cations: the electrometer concept

Changes of the lipid bilayer head group order parameters extracted from simulations and experiments^{10,11} are shown in Figs. 3 and 4 as functions of NaCl or CaCl_2 concentrations. As seen in Fig. 2, the order parameters decrease proportionally to the amount of the bound positive charge. These results can be thus used to compare the ion binding affinities to lipid bilayers between simulations and experiments using the electrometer concept.^{29,30}

The experimentally measured small order parameter changes with NaCl (Fig. 3) are reproduced

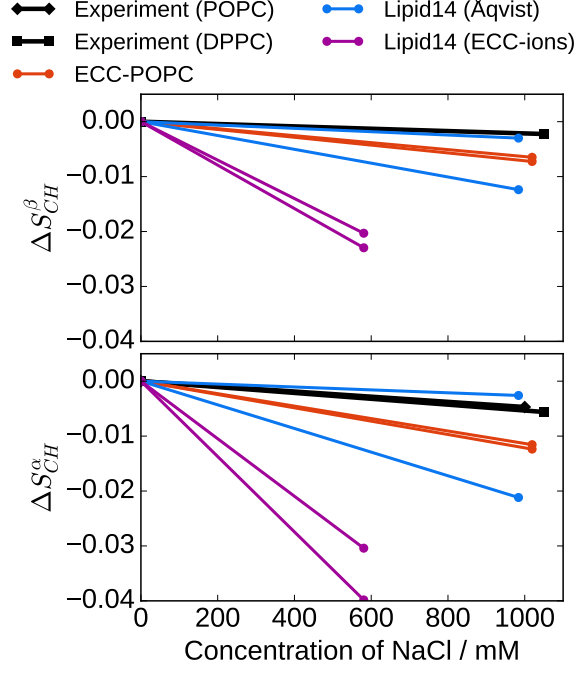


Figure 3: Changes of the head group order parameters of a POPC bilayer as a function of NaCl concentration in bulk (C_{ion}) from simulations with different force fields at 313 K together with experimental data for DPPC (323 K)¹⁰ and POPC (313 K).¹¹ Simulation data with Lipid14 and Åqvist ion parameters at 298 K are taken directly from Refs.^{73,76}

by the Lipid14 model simulated with Åqvist ions. However, the same combination of models overestimates the order parameter changes with CaCl_2 (Fig. 4). Replacing Åqvist ions with ion parameters by Dang et al.^{69–71} or ECC-ions^{32,33,35} did not improve the results (Figs. 3 and 4). In line with the previous work,²⁹ the results suggest that improvements in the lipid parameters are required to correctly describe the binding of cations to phospholipid bilayers.

The results from simulations combining the ECC-POPC with the ECC-ion models^{32,33,35} exhibit a significantly improved behavior of the POPC head group order parameters as a function of NaCl or CaCl_2 concentrations, see Fig. 3 and Fig. 4. Considering that we are also able to reproduce the experimental response in systems with known charge density (see above section), we conclude that our ECC model correctly reproduces the binding affinities of Na^+ and Ca^{2+} ions to the POPC lipid bilayer. Also the binding affinity of K^+ ions to POPC bilayer is in line with the experimental data^{12,99,100} (shown in SI). Furthermore, while the response of the glycerol backbone g_3 order

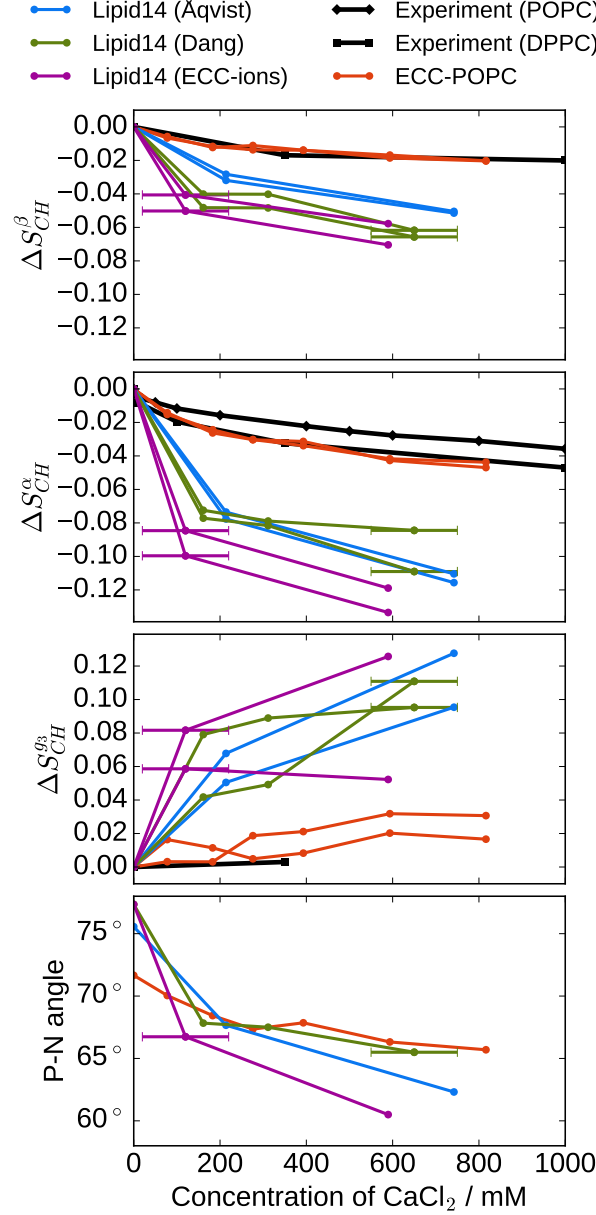


Figure 4: Changes of the head group order parameters and P-N vector orientation of a POPC bilayer as a function of the CaCl_2 concentration in bulk (C_{ion}) from simulations at 313 K together with experimental data (DPPC (323 K)¹⁰ and POPC (313 K)¹¹). The error estimate for bulk concentrations is approximately 10 mM. The order of magnitude larger error in the simulation with Lipid14 and ECC-ions is due to unconverged bulk densities (shown in Fig. 5) limited by the simulation box. Simulation data with Lipid14 and Åqvist ion parameters at 298 K are taken directly from Refs. 73–75.

parameter to CaCl_2 was significantly overestimated in the original Lipid14 model, the ECC-POPC model provides an improved agreement with experiment, as seen in Fig. 4. Also the changes of the

Table 2: Concentration of Ca^{2+} with respect to water (C'_{ion}), bulk concentrations of Ca^{2+} (C_{ion}), relative surface excess of calcium with respect to water ($\Gamma_{Ca}^{\text{water}}$), and the percentages of Ca^{2+} bound to phosphate or carbonyl oxygens ($r_{\text{PO}_4}^{\text{Ca}^{2+}}$ and $r_{\text{O}_{\text{carb.}}}^{\text{Ca}^{2+}}$) in different POPC bilayer models.

| model | C'_{ion} | C_{ion} / mM | $\Gamma_{Ca}^{\text{water}} / \text{nm}^{-2}$ | $r_{\text{PO}_4}^{\text{Ca}^{2+}}$ | $r_{\text{O}_{\text{carb.}}}^{\text{Ca}^{2+}}$ |
|------------------|------------|-----------------------|---|------------------------------------|--|
| ECC-POPC | 350 | 280 ± 10 | 0.06 ± 0.01 | 99% | 32% |
| Lipid14/Åqvist | 350 | 210 ± 10 | 0.13 ± 0.01 | 100% | 37% |
| Lipid14/Dang | 350 | 160 ± 10 | 0.23 ± 0.03 | 100% | 14% |
| Lipid14/ECC-ions | 350 | 120 ± 100 | 0.35 ± 0.11 | 100% | 23% |

P-N vector angle are too pronounced for the Lipid14 model, for which the largest tilting toward water phase induced by a 780 mM CaCl_2 concentration is approximately 17° . The corresponding value for the ECC-POPC simulation is only 6° (820 mM CaCl_2).

Within the Lipid14 model, the overestimated changes in the lipid headgroup order parameter of POPC as functions of the CaCl_2 concentration arise both from the overestimated binding affinity and the excessive sensitivity of the headgroup tilt to the bound positive charge. It is plausible to assume that the same applies to the other lipid models tested in a previous study,²⁹ which underlines the importance of validation of the lipid headgroup order parameter response to the bound charge.

Finally, the ion binding affinities for the ECC-POPC model with different water models are compared in SI. In general, the performance of ECC-POPC with any of the tested water models is better than that of the original Lipid14 model, with the order parameter changes being slightly overestimated with the four-site water models and with TIP3P model.

Binding affinities of Na^+ and Ca^{2+} cations to the POPC membrane

Binding affinities of Ca^{2+} ions to a POPC bilayer in different simulation models were quantified by calculating the relative surface excess of calcium with respect to water molecules, $\Gamma_{\text{ion}}^{\text{water}}$, from Eq. 4. The values of $\Gamma_{\text{ion}}^{\text{water}}$ from different simulations with the same molar concentration of cations with respect to water ($C'_{ion}=350\text{mM}$) are shown in Table 2. As expected from the changes of the lipid headgroup order parameters in Fig. 4, the relative surface excess of calcium, $\Gamma_{Ca}^{\text{water}} = 0.06 \text{ nm}^{-2}$, is significantly smaller for the ECC-POPC model than for the other models, 0.13--

0.35 nm⁻². Interestingly, the calculated relative surface excess of NaCl at 1 M concentration (ECC-ions³³) using our ECC-POPC model is not only quantitatively but also qualitatively different from CaCl₂ having actually a negative value of $\Gamma_{Na}^{water} = -0.11 \pm 0.01$ nm⁻² (Fig. 5). This means that on average water molecules are preferred to sodium and chloride ions at the membrane-water interface. This is in contradiction with most of the available lipid force fields, which predict a positive surface excess of sodium at PC lipid bilayers.²⁹

Molecular interactions between Na⁺ or Ca²⁺ cations and POPC oxygens

We analyzed the ratio of the number of calcium cations bound to either phosphate or carbonyl moieties and the total number of bound cations in our POPC bilayers as done previously in Ref. 25. A maximum distance of 0.3 nm from any lipid oxygen is used to define a bound calcium. The results from ECC-POPC simulation in Table 2 show that almost all (99%) of the bound Ca²⁺ ions are in direct contact with phosphate oxygens. From these ions, only one third (32%) also interacts with the carbonyl oxygens, while the interaction of calcium ions with carbonyl oxygens only is rare (1%). The most abundant interaction scenarios between Ca²⁺ ions and phosphate oxygens are visualized using the probability density isocontours in Fig. 6. While higher concentrations of CaCl₂ increase the number of contacts per lipid, the distribution of contacts between phosphate and carbonyl oxygens is not affected.

Even though Na⁺ ions do not bind strongly to a POPC bilayer, they still interact mostly with its oxygen moieties. The results from a simulation at a 1 M NaCl concentration show that 55% of Na⁺ ions at the bilayer interact with phosphate oxygens of POPC only and 20% with carbonyl oxygens only, with the remaining 25%, is interacting with both negatively charged groups.

In conclusion, the results suggest that calcium ions bind specifically to the phosphate oxygens, occasionally interacting also with the carbonyls of the PC lipids. This is in a qualitative agreement with previous conclusions from several experimental studies.^{2,12,26–28} However, the present results suggest, in agreement with experiments, an overall weaker binding to the bilayer, in particular with a lower relative binding affinity to the carbonyls than inferred from previous MD simulation

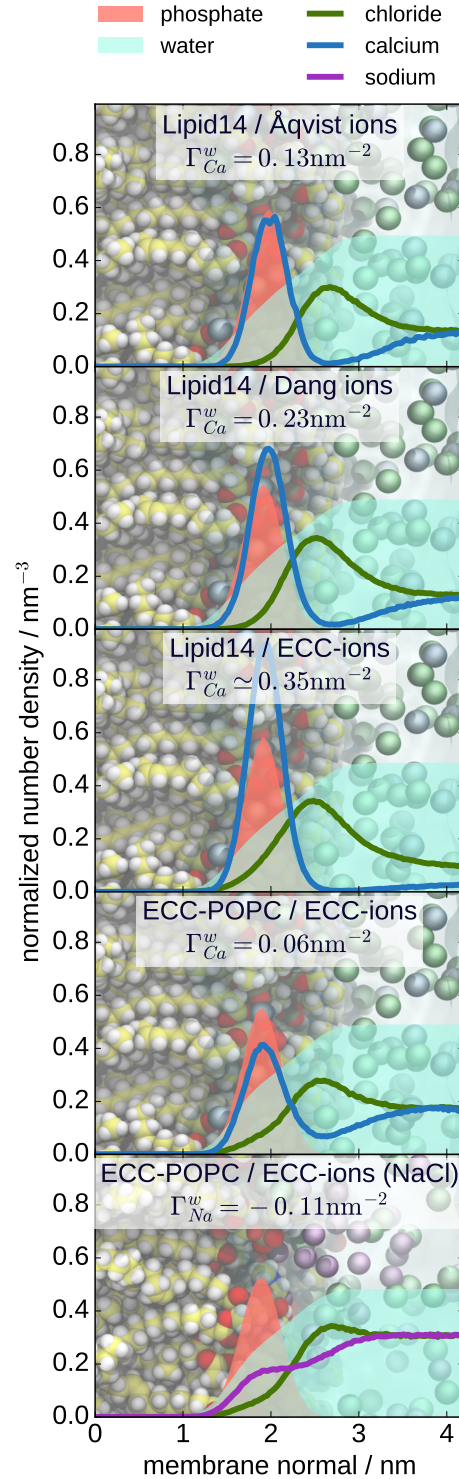


Figure 5: Number density profiles of Ca^{2+} , Na^+ and Cl^- along membrane normal axis for different force fields. In order to visualize the density profiles with a scale comparable to the profile of Ca^{2+} , the density profiles of Cl^- and Na^+ ions are divided by 2, and the density profiles of phosphate groups and water are divided by 5 and 200, respectively. All simulations with CaCl_2 shown here have the same molar concentration of ions in water ($C'_{ion}=350$ mM). The simulation with NaCl has $C'_{ion}=1000$ mM.

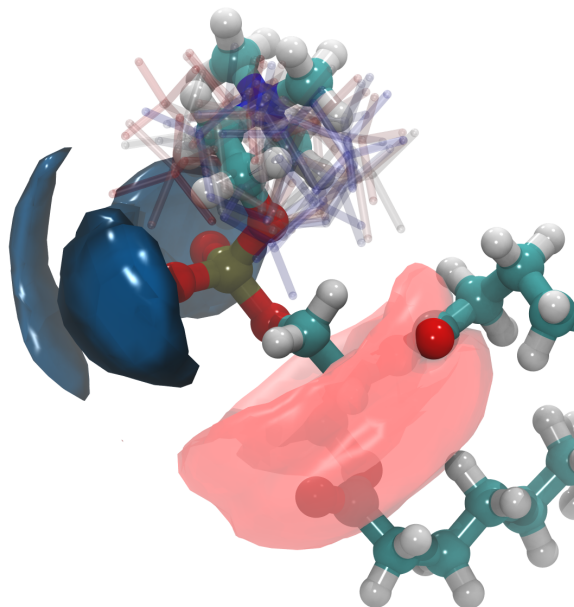


Figure 6: Isocontours of spatial number density of Ca^{2+} (dark blue, 0.001 \AA^{-3}) and POPC carbonyl oxygen atoms (light semi-transparent red, 0.008 \AA^{-3} , all POPC lipids contribute). Calcium cations localize mostly around phosphate oxygens (oxygen red, phosphorus bronze). Interactions with carbonyl oxygens is less likely than with phosphate oxygens, and it is contributed more by other neighbouring phospholipids than by the same lipid. Transparent structures are shown to depict the variability of choline configurations (colour warps from red to blue along the simulation time). The number density was evaluated for each lipid, after its structural alignment using only phosphate group. MDAnalysis¹⁰¹ library was used for the calculations of the structural alignment and the spatial number density. VMD¹⁰² was used for visualisation. Carbon atoms are depicted in cyan, hydrogen atoms in white, oxygen atoms in red, nitrogen in blue.

studies.^{14,15,24,25} Sodium ions, which do not exhibit any appreciable affinity for the bilayer, also interact primarily with phosphate oxygens of the POPC, but in contrast to calcium, the interactions purely with carbonyls are also significant.

Binding stoichiometry of Na^+ and Ca^{2+} cations to POPC membrane

Simple binding models have been used previously to interpret the same experimental data^{11,103} as employed in this work to validate the simulation models (Fig. 4). In particular, NMR data concerning the PC headgroup order parameters response and atomic absorption spectra were explained best using a ternary complex binding model with a binding stoichiometry of one Ca^{2+} per two POPC lipids.¹¹ Nevertheless, a Langmuir adsorption model assuming a Ca^{2+} :POPC stoichiometry of 1:1

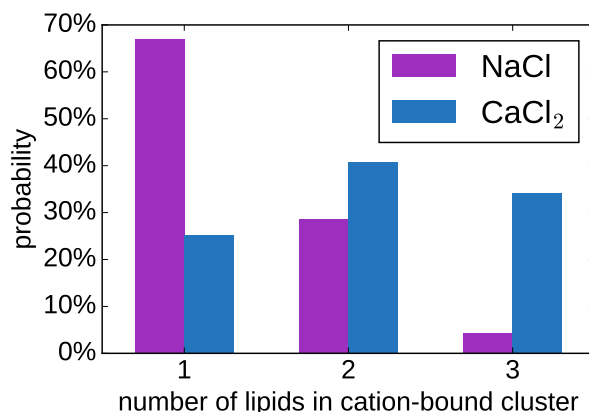


Figure 7: Relative probabilities of existence of Na^+ or Ca^{2+} complexes with a certain number of POPC lipids. Na^+ complexes were evaluated from the simulation with 1 M concentration; and Ca^{2+} complexes were evaluated from the simulation with 287 mM concentration.

also provided a good fit to the experimental data when considering CaCl_2 at low concentrations only.¹⁰³

In this work, we reproduce the same experimental data used to infer binding stoichiometries employing our ECC-POPC model. Thanks to our simulations, we have a direct access to atomistic details of the binding stoichiometry without a need for any binding model as employed for interpreting in experiments.^{11,103} To evaluate the relative propensities for each of the stoichiometric complexes (i.e., 1 Ca^{2+} : n POPC), we calculated for each bound Ca^{2+} the number of POPC molecules having oxygen atoms within a distance of 0.3 nm. Results from the POPC bilayer simulation with a 285 mM bulk concentration of CaCl_2 are shown in Fig. 7. We found the largest propensity for the 1:2 complex (41%), with probabilities of complexes with the stoichiometries of 1:1 (25%) and 1:3 (34%) being only slightly lower. This suggests a more complex binding model than considered in a simple 1:2 ternary complex model previously. Nevertheless, with a broad brushstroke, the simulation data can be viewed such that one calcium binds to two lipids on average, because the probabilities of the complexes with 1 or 3 lipids are almost equal to each other (and complexes with more than three lipids per one calcium ion were not observed). This probably explains why the simple ternary complex model fits adequately the experimental data, as well as the ECC-POPC simulation results (see Fig. S3 in SI).

The probabilities of different complexes formed by Na^+ ions and POPC analyzed from the simulation with the ECC-POPC model at 1 M concentration of NaCl are also shown in Fig. 7. In contrast to calcium, the probability is largest (67%) for 1:1 complex, significantly smaller (29%) for 1:2 complexes and very small (4%) for 1:3 of $\text{Na}^+:\text{POPC}$ complexes.

Residence times of Na^+ and Ca^{2+} cations in the POPC membrane

Equilibration of Ca^{2+} ions at a POPC bilayer in MD simulations is a microsecond time scale process with current force fields, such as CHARMM36 and Slipids force fields.²⁵ This suggests that at least several microseconds are required to reach the ion binding/unbinding equilibrium. To quantify the exchange of ions between the membrane and aqueous solution in simulations, we evaluated residence times of ions bound to the membrane. Within our analysis, an ion is considered to be bound when it is within 0.3 nm from any oxygen atom belonging to a POPC molecule.

The histograms of residence times of Ca^{2+} in a POPC bilayer ($C'_{ion} = 450$ mM) from simulations with ECC-POPC and CHARMM36 (simulation from Refs. 25,104) are shown in Fig. S4 in SI. In the CHARMM36 simulation, a significant number of the calcium ions is bound to the membrane for the whole length of the trajectory (800 ns). In contrast, at least an order of magnitude faster bound/unbound calcium exchange is observed within the ECC-POPC model, where 90% of the Ca^{2+} residence times to a POPC membrane are shorter than 60 ns. The longest observed residence time is around 150 ns, which is below the total length of the simulation used for analysis, i.e., 200 ns. Note that these results are in line with the experimental estimate that the residence time of Ca^{2+} at each PC headgroup is less than $10\ \mu\text{s}$.¹¹ Note that the exchange of Na^+ ions at the POPC membrane is yet another order of magnitude faster, with 90% of the residence times smaller than 1 ns and the longest residence time being 6 ns.

In summary, the results from the ECC-POPC model suggest that the exchange of calcium between the POPC bilayer and the solvent occurs within the ~ 100 ns timeframe, which is significantly faster than observed in simulations employing most of the presently available lipid models.²⁵ Sodium cations exhibit an even more rapid exchange between the membrane and the aqueous so-

lution. Our results suggest that simulations with a length of several hundreds of nanoseconds are sufficient to simulate alkali and alkali earth ion binding to phospholipid bilayers in equilibrium when realistic force fields are used. This has not been the case with previous lipid force fields, which overestimate the binding strength of the sodium and, in particular, calcium cations.^{25,29}

Conclusions

In this study, we employed the electrometer concept to demonstrate that the binding of Na^+ and Ca^{2+} ions to a POPC lipid bilayer can be accurately described within a force field MD simulation, provided that electronic polarization is implicitly included via the electronic continuum correction.³¹ This ECC-POPC model is built upon the Lipid14 POPC model³⁶ by scaling the partial charges by a factor of 0.8 and reducing the Lennard-Jones radii by a factor of 0.89 for the head-group, glycerol backbone, and carbonyl atoms. While the structural details of a POPC lipid bilayer in pure water simulated with the newly developed ECC-POPC model agree with experiments with an accuracy comparable to the other state of the art lipid models, the new model in addition reproduces the experimental lipid head group order parameter responses to a cationic surfactant, NaCl, and CaCl_2 at varying concentrations. It thus represents a significant improvement over currently available lipid models, which tend to overestimate cation binding affinities.²⁹ A similar improvement using the ECC procedure is demonstrated for the POPC model of CHARMM36⁵³ in the SI.

The good agreement with experiments enables us to interpret NMR experiments with atomistic details using MD simulations with the ECC-POPC model. In line with previous interpretations of the experimental data,^{12,26–28} Ca^{2+} ions interact mainly with phosphate oxygens, with interactions to the carbonyls being of a secondary importance. However, the stoichiometry of calcium binding is significantly more complicated than the simple ternary complex model, used to interpret NMR data previously, within which one calcium binds to two POPC molecules.¹¹ While complexes with one calcium ion bound to two lipids are the most probable also in the ECC-POPC model,

complexes of one or three lipids per one calcium were observed to be relatively abundant and also almost equally likely to occur. While the success of the simple ternary complex model in fitting NMR data is understandable based on the simulation results, it cannot capture the detailed nature of calcium binding to phospholipid bilayers observed in the present simulation.

Accurate description of cation binding to POPC bilayer paves the way for simulations of complex biochemical systems at cellular membranes with realistically described electrostatic interactions, including a mean-field account for electronic polarization effects. To this end, the compatibility of the ECC-POPC model with existing models for proteins and other biological molecules needs to be verified and, if necessary, further adjustments following the ECC concept to the force fields of the biomolecules interacting with the lipids should be made. In future studies, the ECC concept will be applied also to bilayers composed of other lipids than POPC.

This work can be reached as a repository containing all data and scripts for analysis at Ref. 105.

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Supporting Information Available

The following files are available free of charge.

- SI.pdf: Simulation details and further analysis.

This material is available free of charge via the Internet at <http://pubs.acs.org/>.

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Graphical TOC Entry

